Mon. Not. R. Astron. Soc. **000**, 000–000 (0000) Printed 2 February 2008 (MN LATEX style file v2.2)

On the minimum mass of reionization sources

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arXiv:0712.0738v1 [astro-ph] 5 Dec 2007

2 February 2008

ABSTRACT
By means of carefully calibrated semi-analytical reionization models, we estimate the minimum mass of star-forming haloes required to match the current data. Models which do not include haloes of total mass $M < 10^9 M_\odot$ fail at reproducing the Gunn-Peterson and electron scattering optical depths simultaneously, as they contribute too few (many) photons at high (low, $z \approx 6$) redshift. Marginally acceptable solutions require haloes with $M \approx 5 \times 10^7 M_\odot$ at $z \approx 10$, corresponding to virial temperatures ($\sim 10^4$K) for which cooling can be ensured by atomic transitions. However, a much better match to the data is obtained if minihaloes ($M \sim 10^6 M_\odot$) are included in the analysis. We have critically examined the assumptions made in our model and conclude that reionization in the large-galaxies-only scenario can remain viable only if metal-free stars and/or some other exotic sources at $z > 6$ are included.

Key words: intergalactic medium cosmology: theory large-scale structure of Universe.

1 INTRODUCTION

Current models of reionization, when compared with QSO absorption line measurements and CMB polarization experiments, seem to indicate that reionization is a complex process extending over $6 < z < 15$. However, the sources which were primarily responsible for the process still remain uncertain. Even if one makes the (not-so-drastic) assumption that reionization is primarily driven by UV photons from stellar sources, the exact nature of the stars and the mass range of the hosting galaxies are still open questions.

For example, semi-analytical models of Choudhury & Ferrara (2006), which are consistent with a wide variety of observational data sets, predict that reionization is mostly driven by haloes of mass $< 10^9 M_\odot$ harboring metal-free stars at $z \approx 10$ (Choudhury & Ferrara 2007). Radiative transfer simulations of Iliev et al. (2007) conclude that the constraints on the electron scattering optical depth $\tau_{\rm el}$ (Spergel et al. 2007) are satisfied by simply including haloes above $10^8 M_\odot$; no exotic sources or minihaloes are required. Using a comprehensive model for galaxy formation, Mao et al. (2007) conclude that the IGM can be completely reionized at $z \approx 6 - 7$ by massive stars within protogalactic spheroids with halo masses $\sim 10^{10} - 10^{11} M_\odot$ without resorting to any special stellar IMF; such models are also found to be consistent with the bounds on $\tau_{\rm el}$. On the other hand, using the observational constraints on the Lyα optical depth at $z = 6$, Bolton & Haehnelt (2007) conclude that the reionization process is "photon-starved" and considerable photon contribution at $z > 6$ is required to complete reionization by $z = 6$. Numerical simulations of Gnedin (2007) predict negligibly small escape of photons from haloes with $M < 10^{11} M_\odot$, and hence it is quite difficult to produce enough photons so as to reionize the IGM by $z = 6$. On the observational front, using the observed value of the assembled mass at $z \simeq 5$ and currently available (but highly uncertain) rate of decline in the star formation history over $5 < z < 10$, it can be concluded that a considerable fraction of star-formation is not yet observed at high redshifts (Stark et al. 2007). This could be either due to significant dust extinction at early times or because of an abundant population of low-luminosity sources just beyond the detection limits of current surveys, thus implying a reionization scenario by small galaxies.

Given such wide variety of conclusions in the literature, it is important to examine in detail the kind of halo masses required to match the available observational data. In particular, it would be interesting to check whether models with only large galaxies (say, haloes with masses $> 10^9 M_\odot$) with standard stellar spectra and IMF are able to match the data, or is there a desperate need for minihaloes ($M \sim 10^6 M_\odot$) and/or metal free (PopIII) stars or any other exotic source. To address this question, we use the semi-analytical formalism of Choudhury & Ferrara (2005) and Choudhury & Ferrara (2006) (hereafter CF05 and CF06 respectively) and consider a series of physically-motivated scenarios which differ in the minimum mass of star-forming haloes. The main idea of this work is to confront each of these scenarios with the QSO absorption line data at $z \approx 6$ and the constraints on $\tau_{\rm el}$ and determine if some of the scenarios can be conclusively ruled out. Throughout the paper, we use the best-fit cosmological parameters from the 3-year WMAP data (Spergel et al. 2007), i.e., a flat universe with $\Omega_m = 0.24$, $\Omega_\Lambda = 0.76$, and $\Omega_b h^2 = 0.022$, and $h = 0.73$. The parameters

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defining the linear dark matter power spectrum are $\sigma_8 = 0.74$, $n_s = 0.95$, $\mathrm{d}n_s/\mathrm{d}\ln k = 0$.

2 BASIC FEATURES OF THE MODEL

The main features of the semi-analytical model used in this work could be summarized along the following (for a more detailed description see CF05 and CF06): The model accounts for IGM inhomogeneities by adopting a lognormal distribution with the evolution of volume filling factor of ionized hydrogen (HII) regions $Q_{\rm HII}(z)$ being calculated according to the method outlined in Miralda-Escudé, Haehnelt, & Rees (2000); reionization is said to be complete once all the low-density regions (say, with overdensities $\Delta < \Delta_{\rm crit} \sim 60$) are ionized. Hence, the distribution of high density regions determines the mean free path of photons

$$\lambda_{\rm mfp}(z) = \frac{\lambda_0}{[1 - F_V(z)]^{2/3}} \quad (1)$$

where F_V is the volume fraction of ionized regions and λ_0 is a normalization constant fixed by comparing with low redshift observations of Lyman-limit absorption systems (Storrie-Lombardi et al. 1994).

The number of ionizing photons depends on the assumptions made regarding the sources. In this work, we have assumed two types of reionization sources:

(i) Stellar sources: We assume that the photon production rate from stars within haloes is proportional to the formation rate of haloes, which in turn is calculated using the Press-Schechter formalism. All haloes above a threshold mass $M_{\rm min}$ are allowed to form stars. The stellar sources are assumed to have metallicities $Z = 0.2 Z_\odot$ and form with a Salpeter IMF in the mass range $1 - 100 M_\odot$; the stellar emission spectra are obtained from the population synthesis models of Bruzual & Charlot (2003).

Under the above assumptions, the characterization of the stellar sources require only two free parameters as far as reionization studies are concerned, namely, (i) the efficiency parameter of stars $\epsilon \equiv \epsilon_* f_{\rm esc}$ where ϵ_* is the fraction of baryonic mass within haloes converted into stars and $f_{\rm esc}$ is the escape fraction of ionizing photons from the host halo and (ii) the minimum mass of haloes $M_{\rm min}$ which are able to form stars. In this work, we assume ϵ to be independent of redshift and halo mass, while different physically-motivated models for $M_{\rm min}$ are chosen and studied, as will be discussed in the next section.

Note that the quantity $M_{\rm min}$ introduced above corresponds to star-forming haloes *only within neutral regions*. Reionization by UV sources is accompanied by photo-heating of the gas, which results in a suppression of star formation in low-mass haloes within ionized regions, a process known as radiative feedback. Hence, the minimum mass of star-forming haloes within ionized regions $M_{\rm min}^{\rm RFB}$ could be substantially larger than $M_{\rm min}$ introduced above. We compute the value of $M_{\rm min}^{\rm RFB}$ self-consistently from the evolution of the gas temperature in the ionized regions and is typically $\sim 2 - 3 \times 10^8 M_\odot$ at $6 < z < 10$.

Note that we do not include any metal-free (i.e. PopIII) stars, which is the main difference of this work compared to our previous works (CF05, CF06).

(ii) QSOs: In this work, we compute the emissivity of QSOs using likelihood estimations of the observed luminosity function at $z < 6$ (Meiksin 2005). The main uncertainty in the QSO contribution comes from the slope of the faint end of the luminosity function which is poorly constrained observationally (Srbinovsky & Wyithe 2007). In this work, we include the contribution of only those QSOs whose luminosities are above the break or characteristic luminosity; hence the QSO contribution should be considered as a lower limit while the actual emissivity could be a few times higher. Our estimates are similar to or lower than that of Meiksin (2005) and Bolton & Haehnelt (2007).

Table 1. Parameter values for different models used in the paper.

Model	$\epsilon = \epsilon_* f_{\rm esc}$
MH	0.008
SH	0.009
LH	0.013

The main observational data sets used in this work are those of the transmitted fluxes F_α and F_β in Lyα and Lyβ regions respectively, as obtained from the QSO absorption spectra. We have taken the points tabulated in Songaila (2004) and Fan et al. (2006). For calculating F_α, we have binned the data points within redshift intervals of $\Delta z = 0.2$ and calculated the mean. The errors are calculated using the extreme values of F_α along different lines of sight. Hence the errors shown in this paper are typically larger than other methods which compute the uncertainties using the interquartile range (Bolton & Haehnelt 2007) or standard dispersion. For calculating F_β, we note that the data points at $z < 5.5$ are quite sparse (Songaila 2004) and hence do not require further binning; we simply use the values and errors tabulated in Songaila (2004). For points at $z > 5.5$, we follow the method identical to the Lyα case. The constraints on $\tau_{\rm el}$ are obtained from Spergel et al. (2007), constraints on $\Gamma_{\rm PI}^{\rm HII}$ from Bolton et al. (2005) and Bolton & Haehnelt (2007) and the redshift distribution of Lyman-limit absorption systems from Storrie-Lombardi et al. (1994).

3 MINIMUM MASS OF STAR-FORMING HALOES

In this Section, we consider three physically motivated models which differ in the choice of the value of $M_{\rm min}$ and check whether they are able to match all the data sets. The models are described in the following:

(i) *Minihalo (MH)*: The minimum mass of star-forming haloes for this model is set by a virial temperature of $T_{\rm vir} = 300$K, which corresponds to a scenario where molecular cooling is fully efficient. Note that $M_{\rm min}$ is redshift-dependent and is typically $\sim 5 \times 10^5 M_\odot$ at $z = 6$. We should mention that the star-forming efficiencies of such haloes are debatable (Haiman & Bryan 2006) as H_2 could be easily dissociated by a Lyman-Werner background photons. However, it has also been argued that such a background only delay the star formation in minihaloes and do not necessarily suppress them (O'Shea & Norman 2007).

(ii) *Small Halo (SH)*: The minimum mass of star-forming haloes is set by a virial temperature of $T_{\rm vir} = 10^4$K; this is motivated by the fact that all haloes having $T_{\rm vir} \geq 10^4$K are able to cool via atomic transitions. This model has $M_{\rm min} \sim 10^8 M_\odot$ at $z = 6$ and is usually considered as standard in most semi-analytical works. We must mention again that for both the SH and MH models, the value of $M_{\rm min}$ corresponds to the neutral regions only; the minimum mass of star-forming haloes is much larger in ionized regions because of radiative feedback.

(iii) *Large Halo (LH)*: The minimum mass of star-forming haloes is set by a virial temperature of $T_{\rm vir} = 5 \times 10^4$K which corresponds to $M_{\rm min}(z = 6) \sim 10^9 M_\odot$. Such value is appropri-

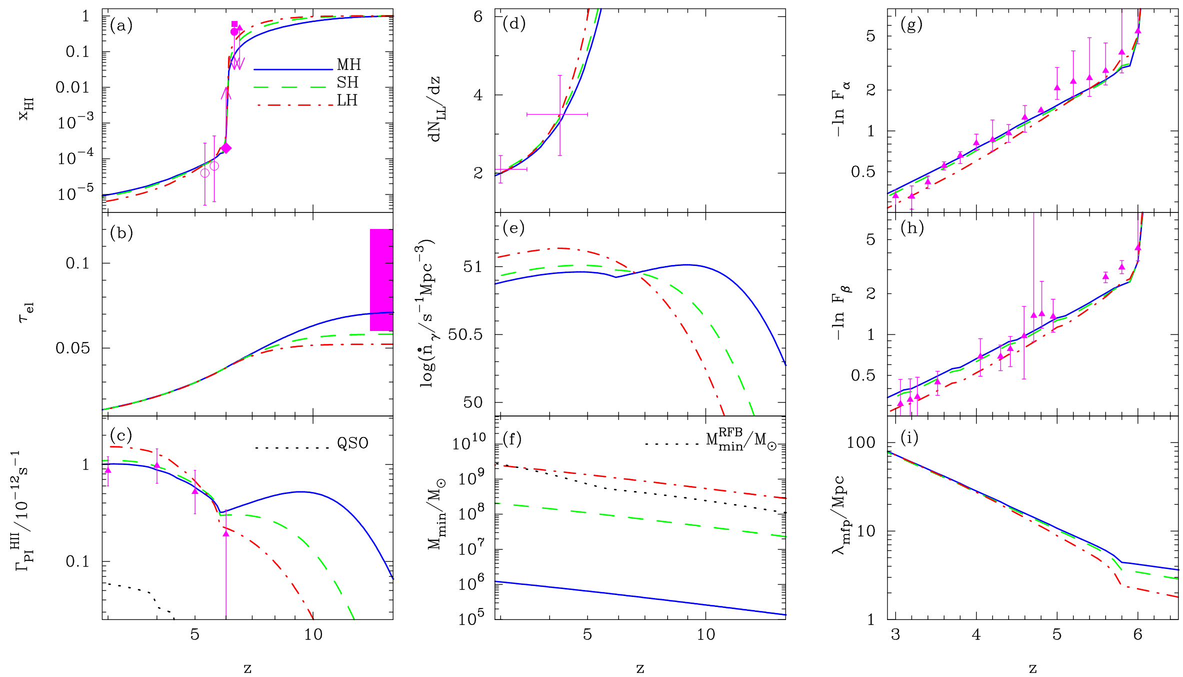

Figure 1. Comparison of model predictions with observations for different models described in the text and summarized in Table 1. The different panels indicate: (a): The volume-averaged neutral hydrogen fraction $x_{\rm HI}$, with observational limits from QSO absorption lines (Fan et al. 2006; diamond), Lyα emitter luminosity function (Kashikawa et al. 2006; triangle) and GRB spectrum analysis (Totani et al 2006; square). Also shown are the constraints using dark gap statistics on QSO spectra (Gallerani et al 2007a; open circles) and GRB spectra (Gallerani et al. 2007b; filled circle). (b): Electron scattering optical depth, with observational constraint from WMAP 3-year data release. (c): Photoionization rates for hydrogen, with estimates from numerical simulations (shown by points with error-bars; Bolton et al. 2005, Bolton & Haehnelt 2007). The dotted line shows the lower limit of the QSO contribution. (d): Evolution of Lyman-limit systems, with observed data points from Storrie-Lombardi et al. (1994). (e): Emission rate of ionizing photons per comoving volume. (f): The minimum mass of haloes which are allowed to form stars within neutral regions. The dotted line denotes the corresponding minimum mass within ionized regions obtained using the radiative feedback prescription. (g): Lyα effective optical depth, with observed data points from Songaila (2004) and Fan et al. (2006). (h): Lyβ effective optical depth, with observed data points from Songaila (2004) and Fan et al. (2006). (i): Evolution of the photon mean free path in physical units.

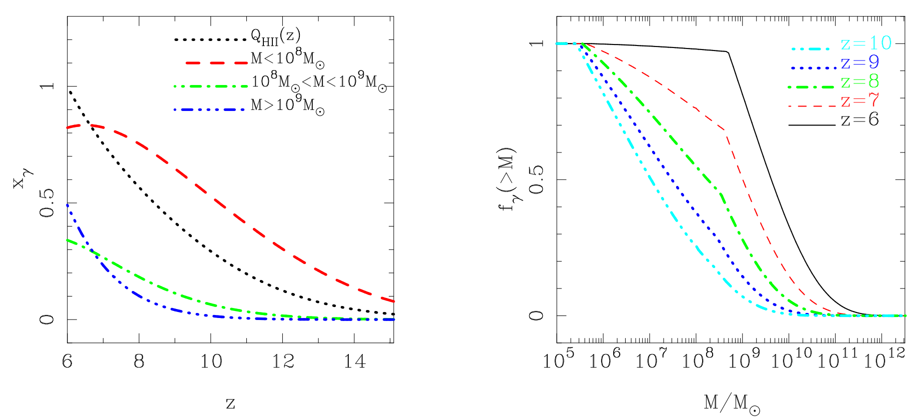

Figure 2. Photon contribution for the MH model. *Left*: Number of ionizing photons per H-atom (accounting for the number of recombinations) contributed by haloes within a given halo mass range as a function of redshift z. The dotted line represents the evolution of the volume filling factor $Q_{\rm HII}$ of ionized regions. *Right*: Cumulative fraction of the ionizing power f_γ contributed by haloes of mass $> M$. The curves from right to left correspond to $z = 6, 7, 8, 9, 10$ respectively.

ate to a scenario in which reionization is driven by large galaxies which are largely unaffected by radiative feedback.

For each model, we find the maximum value of the efficiency ϵ such that it does not violate the upper bound on F_α and F_β at $z = 6$ and then check how it compares with other observations, in particular whether it can produce $\tau_{\rm el} > 0.06$, the 1-σ lower limit from WMAP3 (Spergel et al. 2007). The motivation for normalizing all the models by QSO absorption line data is that the measurements of F_α and F_β are less affected by systematics and other uncertainties compared to other data sets considered here. In contrast, the constraints on $\tau_{\rm el}$ obtained from CMB polarization measurements are still preliminary and the possibility of major revision in future experiments cannot be ruled out. Note that, the lower bounds on F_α and F_β at $z = 6$ are practically zero and hence the minimum value

of ϵ cannot be obtained using QSO absorption line data. However, the upper bounds should be considered as robust; in fact we have been quite conservative in this work and used the extreme maximum value of F_α and F_β allowed by the data. The values of ϵ for different models after normalizing to the upper limits of F_α and F_β at $z = 6$ are summarized in Table 1. The results are shown in Figure 1.

It is clear from the figure that once the models are normalized to the upper bounds on F_α and F_β at $z = 6$, the MH and SH models are able to match the evolution of F_α and F_β up to lower redshifts [Panels (g) and (h)]. However, the LH model, which does not include low mass ($< 10^9 M_\odot$) haloes, gives a poor match with the low redshift observations. Similar conclusions can be drawn from the constraints on $\Gamma_{\rm PI}^{\rm HII}$ where the MH and SH models can fit the data till $z \approx 3$ while the LH model fails to do so. More importantly, when compared with the observed $\tau_{\rm el}$ [Panel (b)], we note that only the MH model can match the data, while the other two models fall short of the lower 1-σ limit. The LH model predicts $\tau_{\rm el} \approx 0.052$, which can be considered as a poor match to the data. The SH model predicts $\tau_{\rm el} = 0.058$, marginally lower than the 1-σ limit; given the uncertainties in the modeling of the reionization, this could be considered as marginally acceptable. Such low value of $\tau_{\rm el}$ is a severe problem for the LH model because the only way to increase the value of $\tau_{\rm el}$ would be to increase ϵ (the only free parameter) which would then underpredict the Lyα and Lyβ optical depths at $z = 6$.

Hence, models which do not include stars from haloes with masses $< 10^9 M_\odot$ cannot match the GP and the electron scattering optical depths simultaneously. In fact, one should at least include haloes of masses $\sim 5 \times 10^7 M_\odot$ to get a marginal match with the data (the SH model). The analysis also brings out the importance of including the QSO absorption line measurements explicitly into any reionization model. For example, a model with only $M > 10^9 M_\odot$ haloes with a efficiency ~ 0.06 would reionize the universe around $z \approx 8$ and produce $\tau_{\rm el} \approx 0.07$; however it would severely overpredict the F_α and F_β (and $\Gamma_{\rm PI}^{\rm HII}$ too) at $z = 6$ and hence would not be acceptable.

Let us examine which haloes contribute most significantly to reionization; we shall limit ourselves to the MH model as the other two models are shown to be unable to match observations. The number of ionizing photons per H-atom contributed by haloes in the mass range $[M_{\rm min}, M_{\rm max}]$ is given by[1]

$$x_\gamma(z) \equiv \frac{n_\gamma(z)}{n_H[1 + t_H(z)/t_{\rm rec}(z)]} \qquad (2)$$

where n_H is the comoving number density of hydrogen atoms while n_γ is the time-integrated comoving photon density, calculated using the relation

$$n_\gamma(z) = \int_0^{t(z)} {\rm d}t \; \dot{n}_\gamma(M_{\rm min} : M_{\rm max}, t) \qquad (3)$$

where $\dot{n}_\gamma(M_{\rm min} : M_{\rm max}, t)$ is the ionizing photon comoving emissivity from haloes within $[M_{\rm min}, M_{\rm max}]$. The term $[1 + t_H(z)/t_{\rm rec}(z)]$ accounts for the number of recombinations in the IGM where $t_H(z)$ is the Hubble time and $t_{\rm rec}(z)$ is the recombination time. By construction, the IGM is reionized when $x_\gamma \gtrsim 1$. A second quantity of interest is the fractional instantaneous contribution of haloes above a certain mass,

$$f_\gamma(> M, z) \equiv \frac{\dot{n}_\gamma(> M, z)}{\dot{n}_\gamma(z)}. \qquad (4)$$

The plots of x_γ and $f_\gamma(> M, z)$ for the MH model is shown in Figure 2. It is clear from the figure that haloes of mass $< 10^8 M_\odot$ dominate the ionizing background at high redshifts, their contribution decreasing gradually at $z < 8$ because of radiative feedback. However, these haloes are still the dominant contributors of ionizing photons when integrated till $z = 6$ (though the instantaneous photon production rate at $z = 6$ is dominated by $> 10^9 M_\odot$ haloes). Hence models which do not include $M < 10^8 M_\odot$ haloes would miss out a large fraction photons at high redshifts (before radiative feedback is effective) and hence would underpredict $\tau_{\rm el}$. For the SH model, we find that $< 10^8 M_\odot$ haloes produce only about 10% of ionizing photons when integrated till $z = 6$, while about 50% of photons come from high mass $> 10^9 M_\odot$ haloes.

4 DISCUSSION

We have used a semi-analytical reionization model, empirically calibrated on a variety of observational data sets, to estimate the minimum mass of ionizing photon sources required to match the current data. We find that models which do not include haloes with mass $M < 10^9 M_\odot$ are not able to reproduce the GP and electron scattering optical depths *simultaneously*. Such models (i) contribute too few photons at high redshift, and (ii) *produce too many photons too late*. To get a marginally acceptable match with the data, one requires haloes with masses as small as $5 \times 10^7 M_\odot$ at $z \approx 10$, which would correspond to a virial temperature of $\sim 10^4$K. In such cases, though the bulk of photons ($\sim 90\%$) is produced by $M > 10^8 M_\odot$ haloes, the low mass haloes are important to contribute to $\tau_{\rm el}$ at high redshifts without violating the QSO absorption line constraints at $z = 6$.

A much better match to the data is obtained if minihaloes ($M \sim 10^6 M_\odot$) are included in the analysis. These haloes produce enough photons at high redshifts to give a high $\tau_{\rm el}$. They are also easily destroyed once radiative feedback becomes substantial and hence give no contribution to the photoionization rate at $z \approx 6$, thus agreeing with the F_α and F_β upper bounds. In case the minihaloes are not allowed to form stars because of some photodissociating Lyman-Werner background, it becomes almost impossible to construct reionization models with standard stellar sources that are not in tension with data. Given this, it is crucial to critically examine the assumptions and idealizations made in our formalism which could allow reionization scenarios with only large galaxies to be consistent with the data, which is done in the following:

(i) z-dependence of the photon production efficiency: in this work, we have assumed the efficiency parameter ϵ, the stellar IMF and the stellar spectrum to be independent of z. In case the value of ϵ was higher at high redshifts, it could, in principle, produce high $\tau_{\rm el}$ at high redshifts without violating the GP constraints at $z = 6$. Such behavior of ϵ would mean that either stars were forming more efficiently at early times and/or the escape fraction of photons was higher. A similar effect could also be achieved if the stellar IMF was top-heavy at high-z or the spectra of the stars were harder. In short, one would require a very efficient production of photons per baryons at high-z. An obvious candidate for achieving such effects would be the inclusion of metal-free (PopIII) stars with or without a top-heavy IMF. Such models with PopIII stars are found to be an excellent match to a wide variety of data sets in the SH scenario

[1] Note that, in our previous work, we had defined $x_\gamma(z)$ as $\frac{n_\gamma(z)}{n_H}\frac{t_{\rm rec}(z)}{t_H(z)}$, which blows up when recombinations are negligible ($t_{\rm rec} \to \infty$). Under the present definition, $x_\gamma(z) \to \frac{n_\gamma(z)}{n_H}$ when $t_{\rm rec} \to \infty$, which is the correct limit.

(CF06), while they can possibly be tuned to match the data in the LH case too.

(ii) Mass-dependence of ϵ: similarly neglected here, is the possibility that the efficiency parameter depends on the halo mass. Note that, in order to make the LH scenario work, one would require ϵ to be higher for smaller mass haloes so that the photon contribution increases at $z > 6$. However, the mass-dependence, if any, is found to be opposite, e.g., Kauffmann et al. (2003) found that ϵ increases with halo mass for $M < 3 \times 10^{12} M_{\odot}$ in the local Universe. Given this, it is unlikely that a mass-dependent ϵ would improve the performance of large-galaxy-only models.

(iii) Radiative feedback: One of the main uncertainties in theoretical models of reionization is the implementation of radiative (i.e. photoionization) feedback. However, note that this effect mostly affects haloes of masses $< 10^9 M_{\odot}$ [Panel (f) of Figure 1] and hence a different feedback prescription would have *no* effect on the LH model at all. For the SH model, a less severe feedback mechanism, which allows the $10^8 M_{\odot} < M < 10^9 M_{\odot}$ haloes to survive longer than what is used here (Gnedin 2000), could produce enough photons at high-z to get a better match to the data. On the other hand, if the feedback is more severe on the $\sim 10^8 M_{\odot}$ haloes (e.g., because of the photoionization rate boost arising from the clustering of galaxies, and not taken into account here), the SH model would be ruled out.

(iv) QSOs: The contribution of QSOs considered here should be thought of as a lower limit; the actual contribution could be much higher. However, this does not affect our conclusions because a higher contribution from QSOs at $z \sim 6$ would imply a lower value of ϵ, which would then produce a much lower $\tau_{\rm el}$.

(v) IGM inhomogeneities: The density distribution of the IGM has been assumed to be lognormal, which is found to be a good match to the QSO transmitted flux distribution (Gallerani, Choudhury, & Ferrara 2006). However, it has been argued that the density distribution obtained from simulations has a different form (Miralda-Escudé, Haehnelt, & Rees 2000). The density distribution can affect the results in three ways, namely: (a) The evolution of $Q_{\rm HII}(z)$ could be altered if the density distribution is different; however note that there is not much freedom observationally in the qualitative behavior of $Q_{\rm HII}(z)$ as QSO absorption line data requires reionization to be completed around $z \gtrsim 6$. (b) The evolution of $\lambda_{\rm mfp}$ could be different thus modifying the photoionization rate $\Gamma_{\rm PI}^{\rm HII}$ which is discussed in the next point. (c) For a given $\Gamma_{\rm PI}^{\rm HII}$, a different density distribution would give a different the value of F_{α} (and F_{β}). However, note that the analysis presented in the paper could also be done using the constraints on $\Gamma_{\rm PI}^{\rm HII}$ without any reference to F_{α} or F_{β}, and the results would still be qualitatively similar.

(vi) Photon mean free path: A related problem is that regarding the value of $\lambda_{\rm mfp}$ at $z = 6$. There are no observational constraints on $\lambda_{\rm mfp}$ at $z > 4$, and the theoretical estimates would depend on the density distribution of the IGM. In case $\lambda_{\rm mfp}$ is found to be lower than that obtained in our models ($\lambda_{\rm mfp}(z = 6) = 3.73$ and 2.37 proper Mpc for SH and LH respectively), it would give a lower $\Gamma_{\rm PI}^{\rm HII}$ for the same value of ϵ, and hence could allow the SH and LH models to match with observations. However, the typical values of $\lambda_{\rm mfp}$ found using the density distribution of Miralda-Escudé, Haehnelt, & Rees (2000) are ~ 5 physical Mpc (Bolton & Haehnelt 2007; Wyithe, Bolton, & Haehnelt 2007), which would clearly rule out the SH and LH models. A trivial extrapolation of the observed $\lambda_{\rm mfp}$ at lower redshifts to high-z would too give similar values.

(vii) Revised observational constraints: A good chance of the large galaxies scenario to survive (without including PopIII stars or other sources) would be to revise the constraints on $\tau_{\rm el}$. We have already seen that the value of $\tau_{\rm el}$ was lower in the WMAP3 data release than in the WMAP1 because of systematics. In case the value of $\tau_{\rm el}$ is found to be ~ 0.05, it would be enough to allow the LH scenario. On the other hand, in case the upper bounds on F_{α} and F_{β} are tightened with increase in QSO sample size, it could rule out the LH (and possibly SH) scenario with a higher degree of confidence. For example, we have been conservative in estimating the errors and allowed a F_{α} as high as 0.0125 at $z = 6$. One should compare this with the constraints $F_{\alpha} < 0.004$ used by Bolton & Haehnelt (2007); such severe constraints would clearly disfavor the LH and SH scenarios. Another possibility is that the constraints on the cosmological parameters are revised, e.g., the value of σ_8 is found to be higher than what is used. A rigorous exploration of the cosmological parameter space is beyond the scope of this work. However, a model with higher value of $\sigma_8 = 0.9$ (Viel, Haehnelt, & Lewis 2006), when normalized to Lyα and Lyβ flux at $z = 6$, gives $\tau_{\rm el} \approx 0.059$; this value is still well below the corresponding 1-σ bound on $\tau_{\rm el} \approx 0.1 \pm 0.03$.

In spite all the model uncertainties, it seems certain that reionization with large galaxies scenario ($M > 10^9 M_{\odot}$) can be conclusively ruled out with the present data; such scenarios can only be allowed if metal-free stars or other exotic sources at high redshifts are included. The scenario where only those haloes which can cool via atomic transitions contribute is marginally acceptable. In any case, there seems to be a requirement for a large number of sources at $z \approx 10$, which are most likely faint (i.e., low-mass) haloes. Observationally, it is important to put constraints on star formation within these faint galaxies at high redshift which, however, seems to be a challenging task. Nonetheless one should be optimistic as most of such issues would be addressed with future experiments like JWST. On the theoretical front, it is important to realize that reionization models could be incomplete unless they are compared with both the $\tau_{\rm el}$ and GP constraints simultaneously.

ACKNOWLEDGEMENT

SG acknowledges the support by the Hungarian National Office for Research and Technology (NKTH), through the Polányi Program.

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